

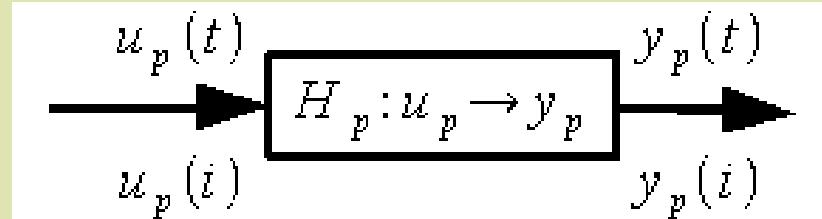
A Passivity-Based Framework for Resilient Cyber Physical Systems

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Passive Systems



Are a special-class of conic systems inside the sector $[a, b]$

$$0 \leq a < b \leq \infty$$

$$\int_0^{NT_s} y_p^T(t) y_p(t) dt - (a+b) \int_0^{NT_s} y_p^T(t) u_p(t) dt + ab \int_0^{NT_s} u_p^T(t) u_p(t) dt \leq 0$$

$$\| (y_p)_{NT_s} \|_2^2 - (a_p + b_p) \langle y_p, u_p \rangle_{NT_s} + a_p b_p \| (u_p)_{NT_s} \|_2^2 \leq 0$$

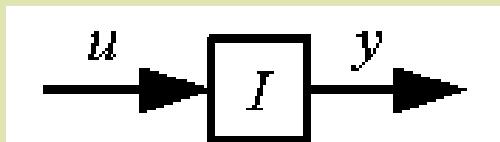
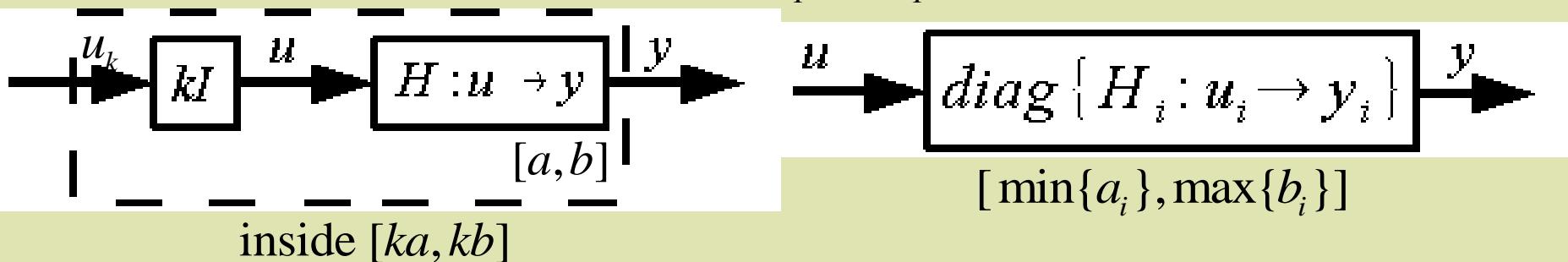
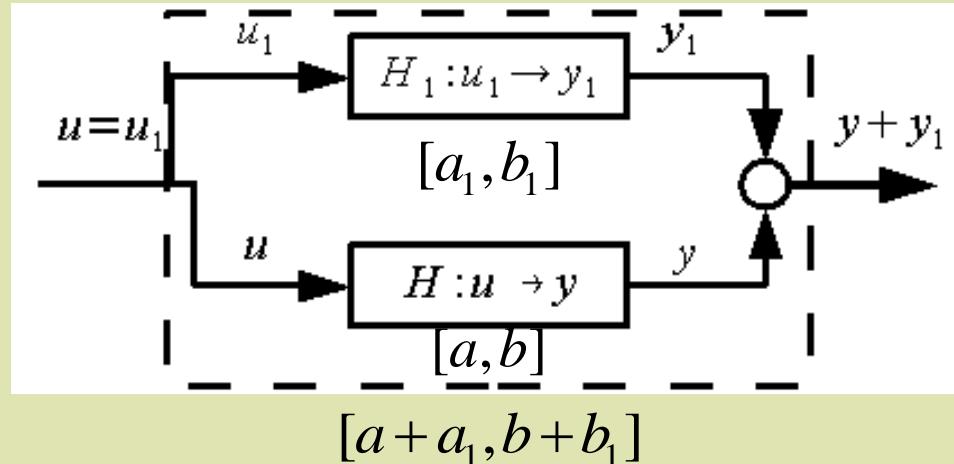
passive inside the sector $[0, \infty]$,

strictly input passive inside the sector $[a, \infty]$ $a > 0$,

strictly output passive inside the sector $[0, b]$ $b < \infty$.



Passive Systems Properties



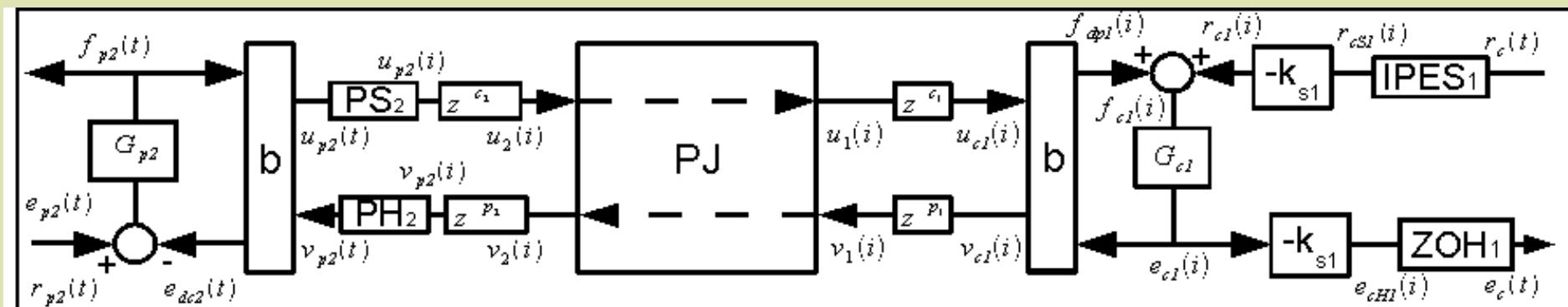
$[1, 1] \rightarrow \text{strictly inside } [0, 1 + \epsilon], \epsilon > 0, [\epsilon, 1] \rightarrow -1 \leq \epsilon \leq 1$

Digital Passive Attitude and Altitude Control Schemes for Quadrotor Aircraft (Kottenstette, Porter: to appear ICCA'09)



L^m_2 -Stable Digital Control Network

If $G_{p2} : e_{p2} \rightarrow f_{p2}$ is inside $[0, b_{p2}]$ and $G_{c1} : f_{c1} \rightarrow e_{c1}$ is inside $[0, b_{c1}]$ and delays... then denoting $y^T = [f_{p2}^T, e_{c2}^T]$, $r^T = [r_{p2}^T, r_{c1}^T]$ $H : r \rightarrow y$ is inside $[0, b]$ ($b = \max\{b_{p2}, T_s k_{s1}^2 b_{c1}\}$).



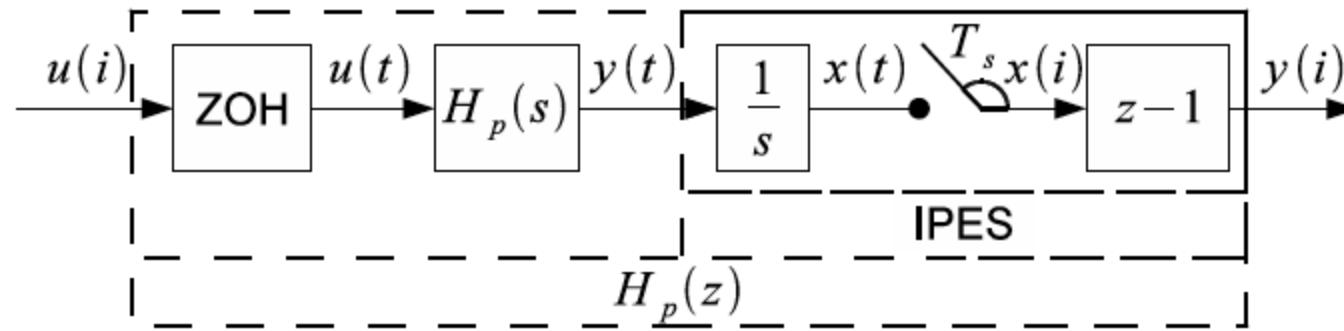
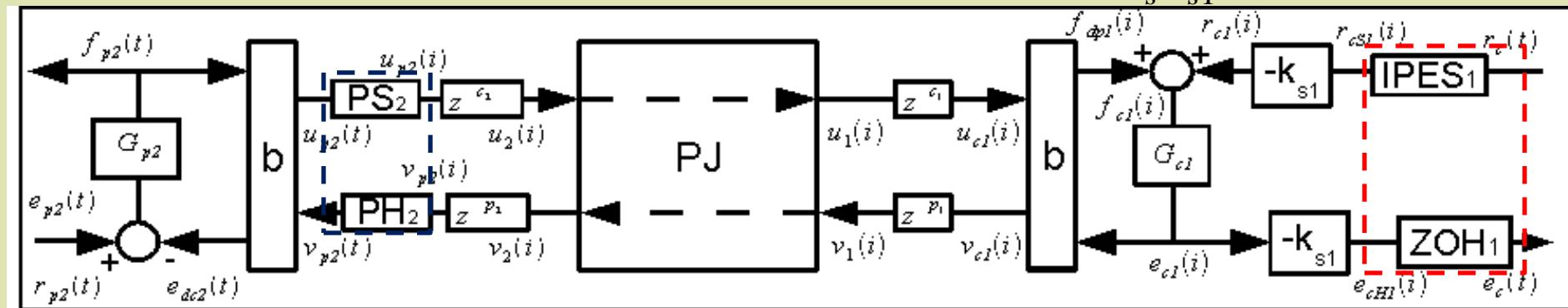
Design of Networked Control Systems Using Passivity
(Kottenstette, Hall, Koutsoukos, Sztipanovits, Antsaklis, under review TPDS)



IPESH-Transform

inner-product equivalent sampler (IPES) and zero-order-hold (ZOH), (IPESH) great for analysis and synthesis.

$$\langle e_{c1}(i), r_{c1}(i) \rangle_N = \langle e_{c1}(t), r_{c1}(t) \rangle_{NT_s}, \quad \| (e_{c1}(i))_N \|_2^2 = \frac{1}{T_s k_{s1}^2} \| (e_{c1}(t))_{NT_s} \|_2^2$$

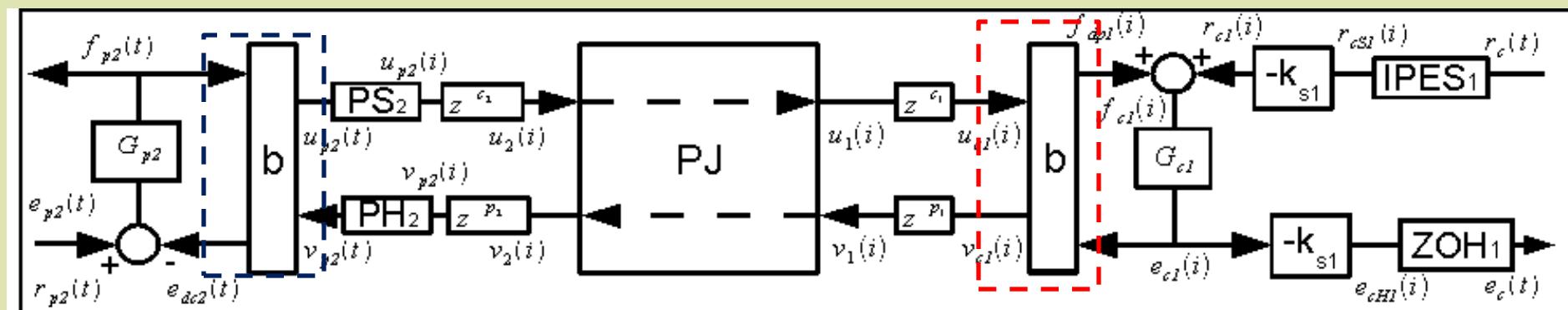




Bilinear Transform w/ Wave Variables

$$\begin{bmatrix} u_{p2}(t) \\ e_{dc2}(t) \end{bmatrix} = \begin{bmatrix} -I & \sqrt{2b}I \\ -\sqrt{2b}I & bI \end{bmatrix} \begin{bmatrix} v_{p2}(t) \\ f_{p2}(t) \end{bmatrix}$$

$$\begin{bmatrix} v_{c1}(i) \\ f_{dp1}(i) \end{bmatrix} = \begin{bmatrix} I & -\sqrt{\frac{2}{b}}I \\ \sqrt{\frac{2}{b}}I & -\frac{1}{b}I \end{bmatrix} \begin{bmatrix} u_{c1}(i) \\ e_{c1}(i) \end{bmatrix}$$



$$\frac{1}{2} [u_{p2}^T(t)u_{p2}(t) - v_{p2}^T(t)v_{p2}(t)] = f_{p2}^T(t)e_{dc2}(t)$$

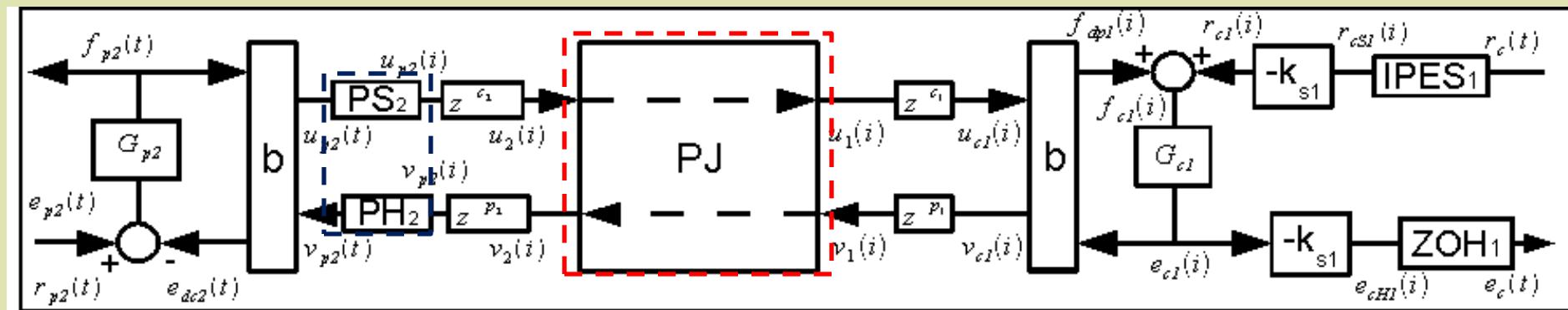
$$\frac{1}{2} [u_{c1}^T(i)u_{c1}(i) - v_{c1}^T(i)v_{c1}(i)] = f_{dp1}^T(i)e_{c1}(i)$$



PS-PH “inside” [-1,1]

Passive Sampler (PS) and Passive Hold (PH) provide a causal tool to transform a continuous-time signal to a discrete-time signal:

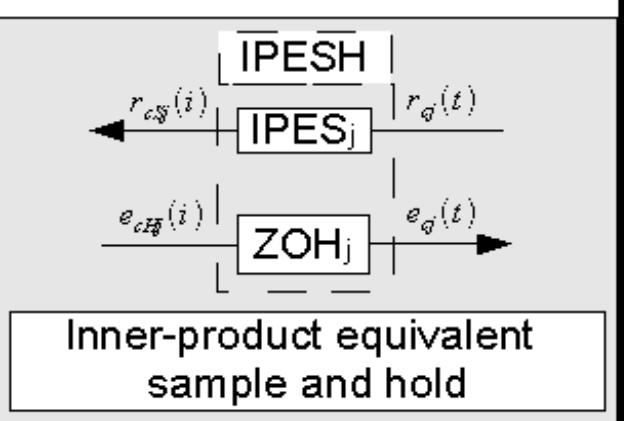
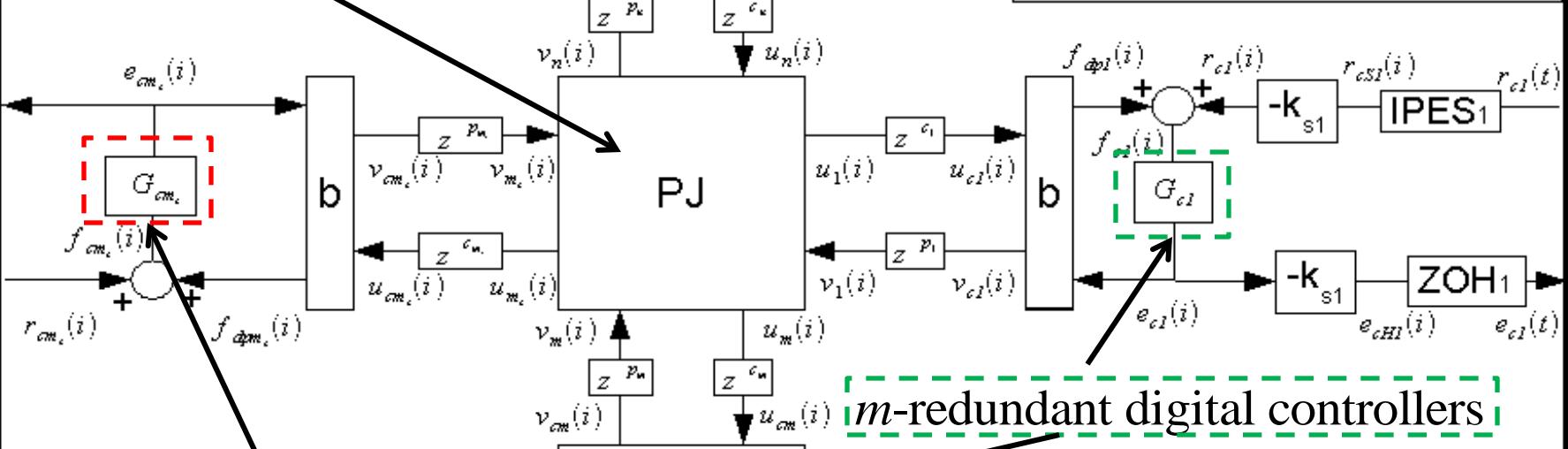
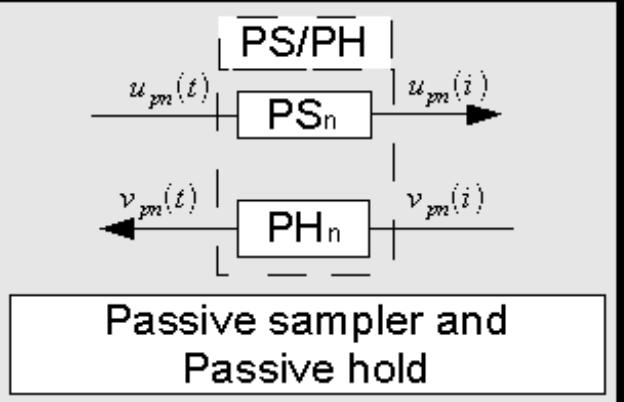
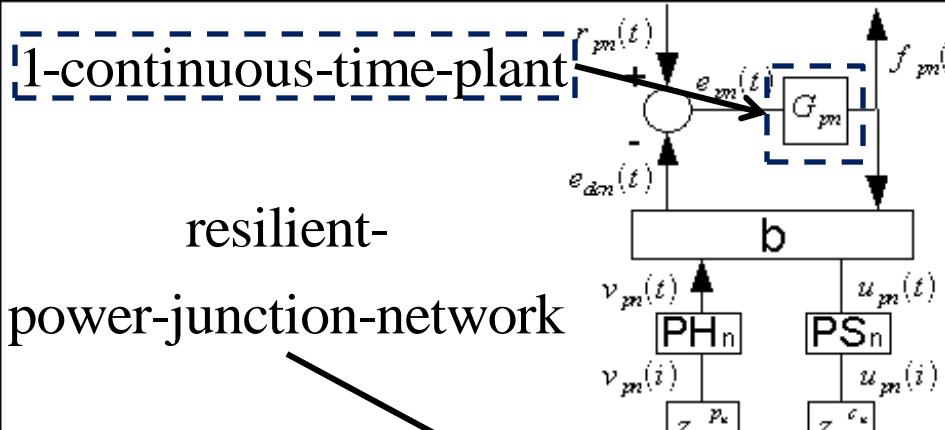
$$\|(\mathbf{u}_{p2}(i))_N\|^2 \leq \|(\mathbf{u}_{p2}(t))_{NT_s}\|^2, \quad \|(\mathbf{v}_{p2}(t))_{NT_s}\|^2 \leq \|(\mathbf{v}_{p2}(i))_N\|^2$$



Simple power-junction-network $u_1(i) = u_2(i)$, $v_2(i) = v_1(i)$: an io-wave-variable-network, total-wave-power-in \geq total-wave-power-out.

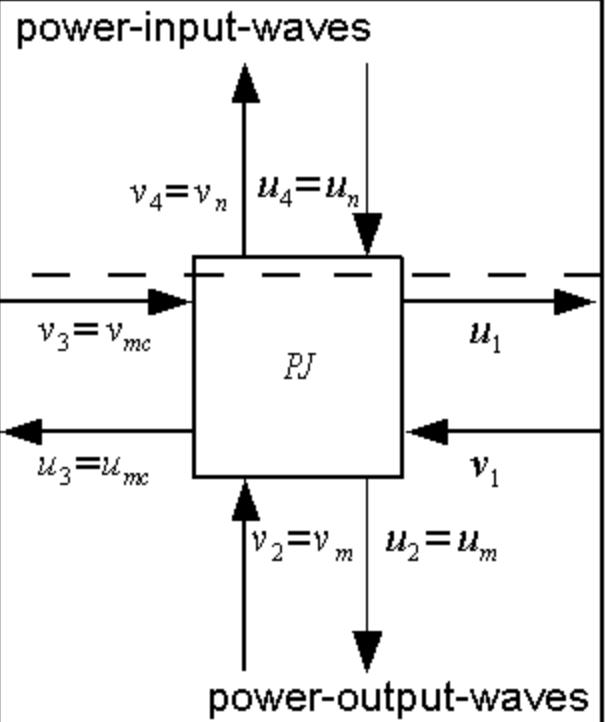
$$u_2^\top u_2 - v_2^\top v_2 \geq u_1^\top u_1 - v_1^\top v_1$$

resilient-
power-junction-network





Resilient-power-junction-network



Special-type of power-junction-network for
1 – plant, m_c – controllers in which
 m are redundant, insures that
total-wave-power-in \geq total-wave-power-out

$$u_n^\top u_n - v_n^\top v_n \geq \sum_{j=1}^{m_c} u_j^\top u_j - v_j^\top v_j, \quad n = m_c + 1$$



Resilient-power-junction-network

Est. \hat{m} redundant controllers (ie. $\hat{m} = m_c$)

$$u_1 = \dots = u_{\hat{m}} = \frac{1}{\hat{m}} u_n, \quad u_j = v_j, j = \hat{m} + 1, \dots, m_c$$

if all delays equal, detect non-redundant, update \hat{m}

$$\text{sf}_v = \frac{\left| \sum_{j=1}^{\hat{m}} v_{j_l} \right|}{\sum_{j=1}^{\hat{m}} |v_{j_l}|} \leq 1 \quad , \quad v_{n_l} = \text{sf}_v \operatorname{sgn} \left(\sum_{j=1}^{\hat{m}} v_{j_l} \right) \sqrt{\sum_{j=1}^{\hat{m}} v_{j_l}^2}$$



Case Study

classic velocity control of dc-motor

$$G_{pn}(s) = \frac{k_{pn}}{s + \omega_{pn}} = \frac{2}{s + 5}$$

Synthesize digital-PID-like-controller
by applying IPESH-Transform to

$$G_{cj}(s) = k_p + \frac{k_I}{s + \varepsilon k_I} + k_D \frac{\frac{NT_s}{\pi} s + 1}{\frac{T_s}{\pi} s + 1}, \quad \varepsilon > 0, N > 1.$$

$$G_{cj}(z) = k_p + \frac{k_I T_s}{2 + \varepsilon k_I T_s} \frac{z + 1}{z + \frac{-2 + \varepsilon k_I T_s}{2 + \varepsilon k_I T_s}} + k_D \left(1 + \frac{T_s(N-1)}{\pi} H_D(z) \right)$$
$$H_D(z) = \frac{1-p}{T_s} \frac{z-1}{z-p}, \quad p = \exp(-\pi)$$



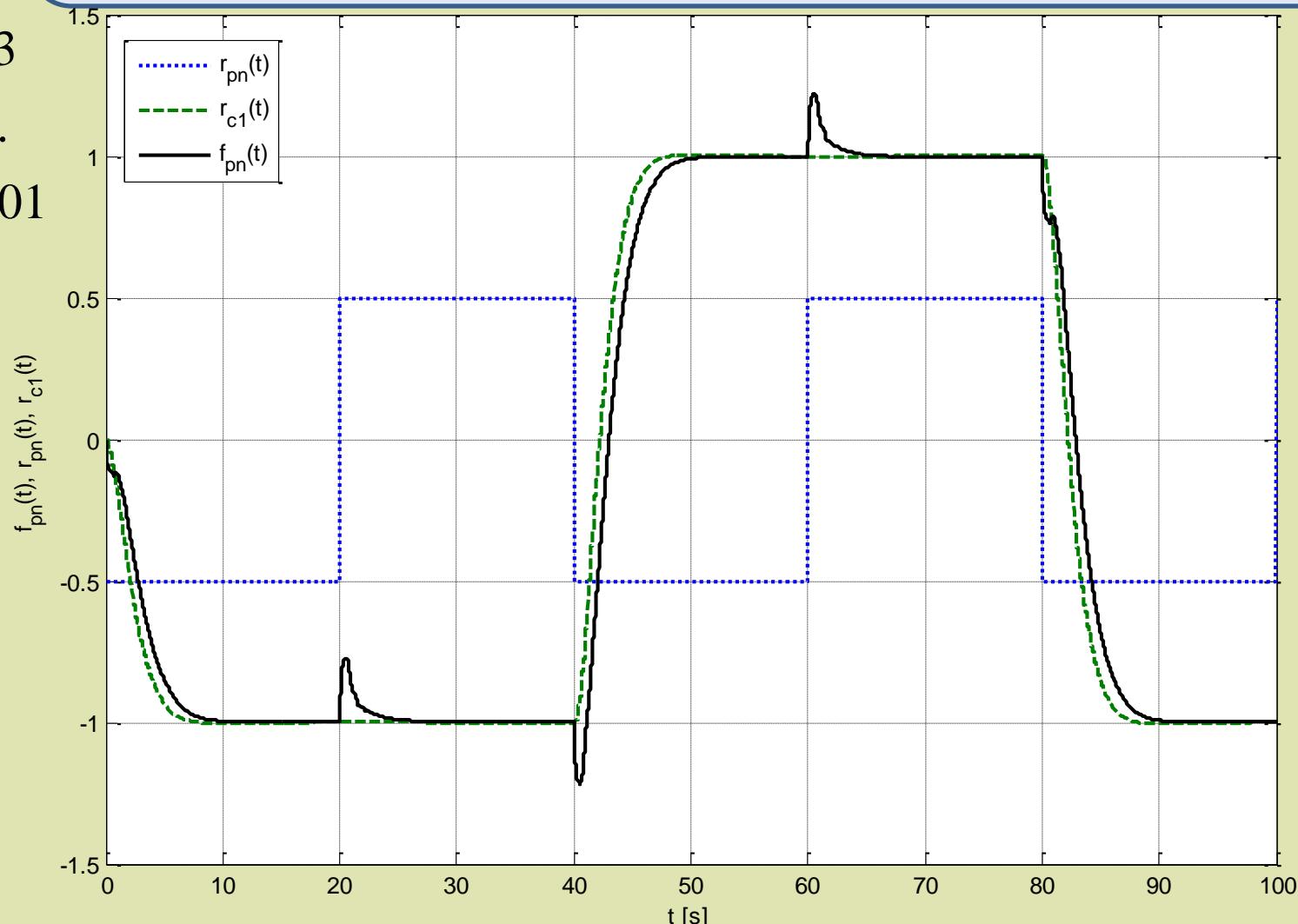
Nominal Response

$$m = m_c = 3$$

$$T_s = .1 \text{ sec.}$$

$$b=2, \varepsilon=.001$$

$$N=10$$





Single Controller Integrator Failure

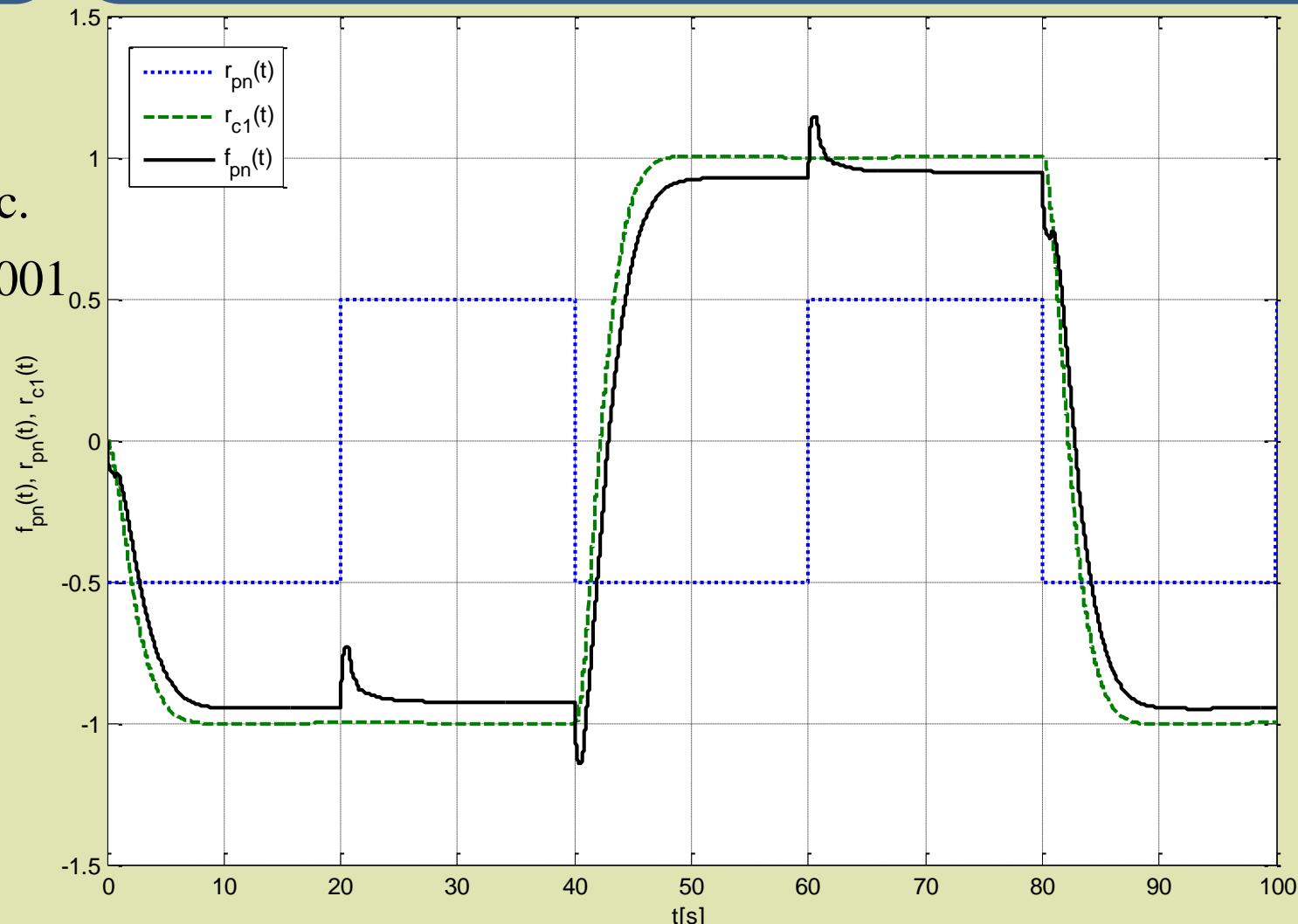
$$m_c = 3$$

$$m = 2$$

$$T_s = .1 \text{ sec.}$$

$$b=2, \varepsilon=.001$$

$$N=10$$





DOS Attack on Single Controller

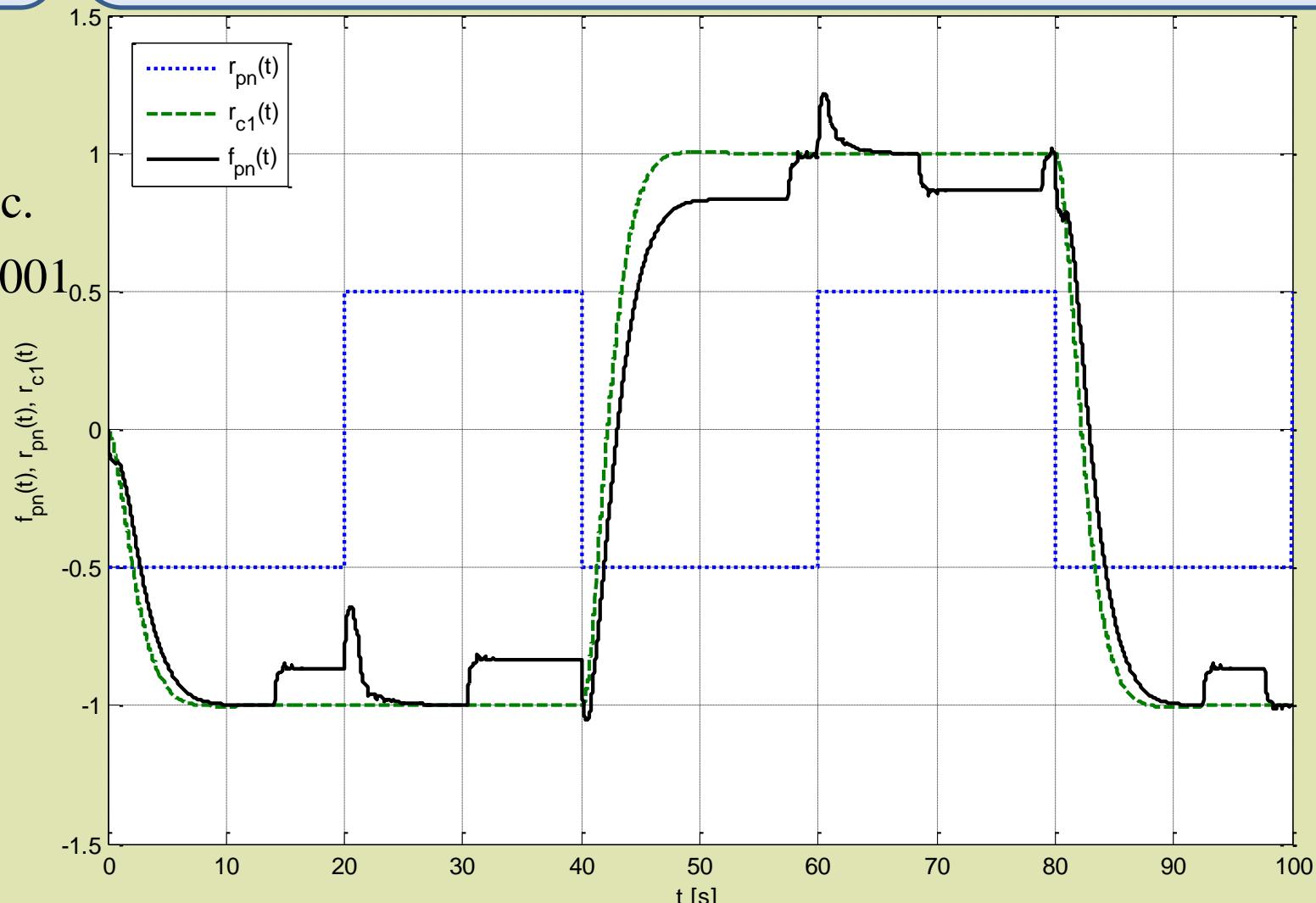
$$m_c = 3$$

$$m = 2$$

$$T_s = .1 \text{ sec.}$$

$$b=2, \varepsilon=.001$$

$$N=10$$





(undetected) Destabilizing controller introduced

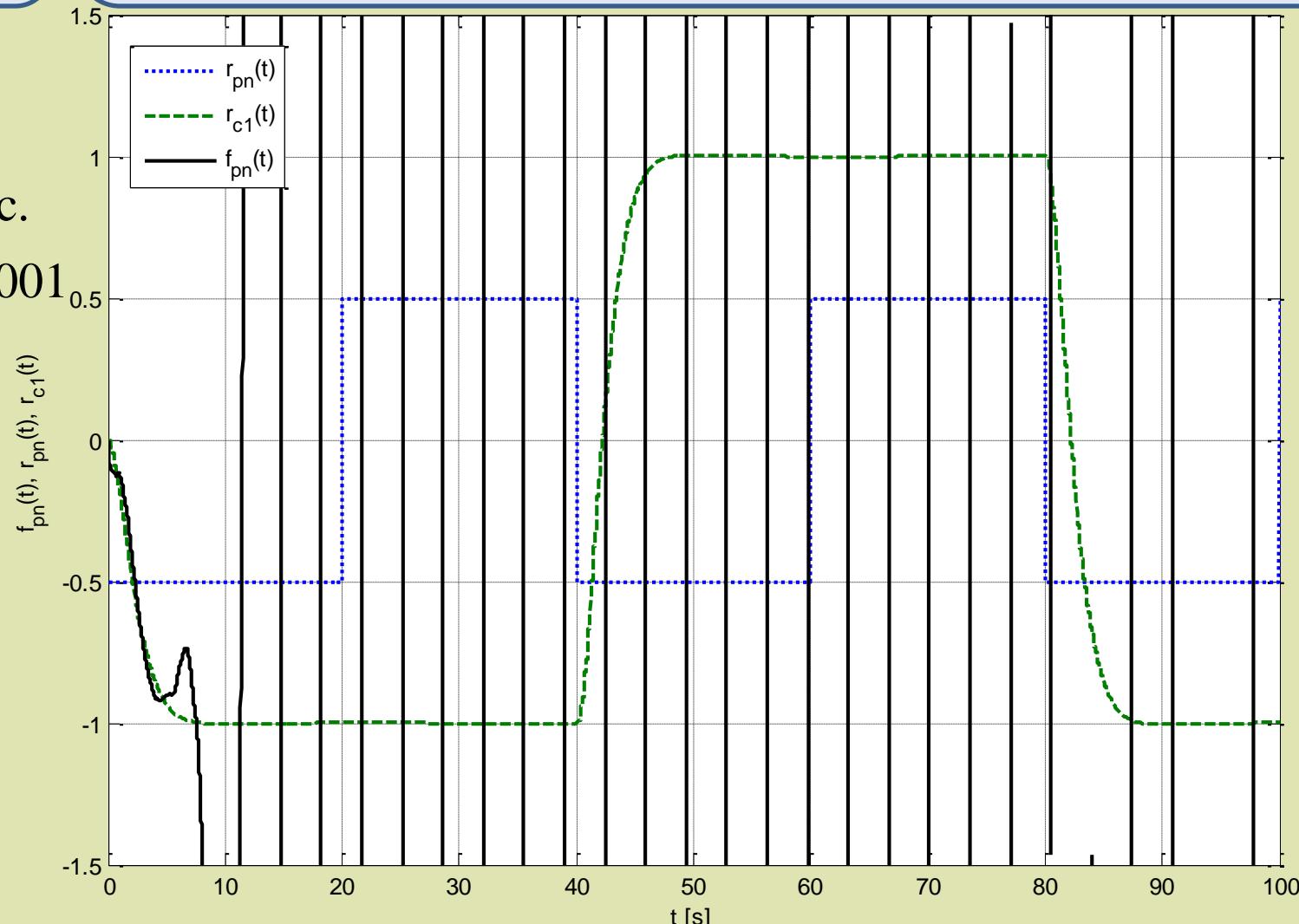
$$m_c = 3$$

$$m = 2$$

$$T_s = .1 \text{ sec.}$$

$$b=2, \varepsilon=.001$$

$$N=10$$





Destabilizing controller detected and isolated

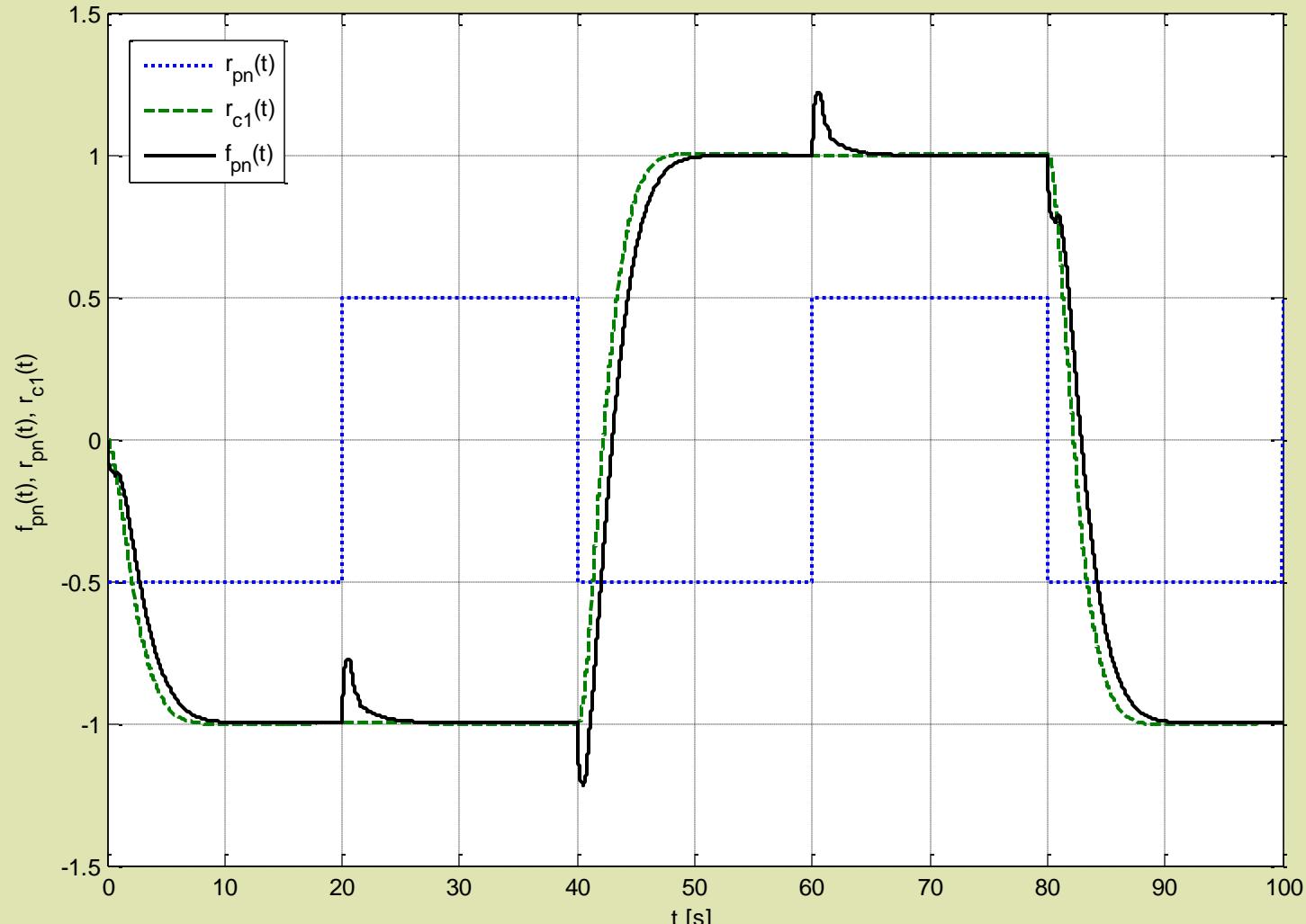
$$m_c = 3$$

$$m = 2$$

$$T_s = .1 \text{ sec.}$$

$$b=2, \varepsilon=.001$$

$$N=10$$



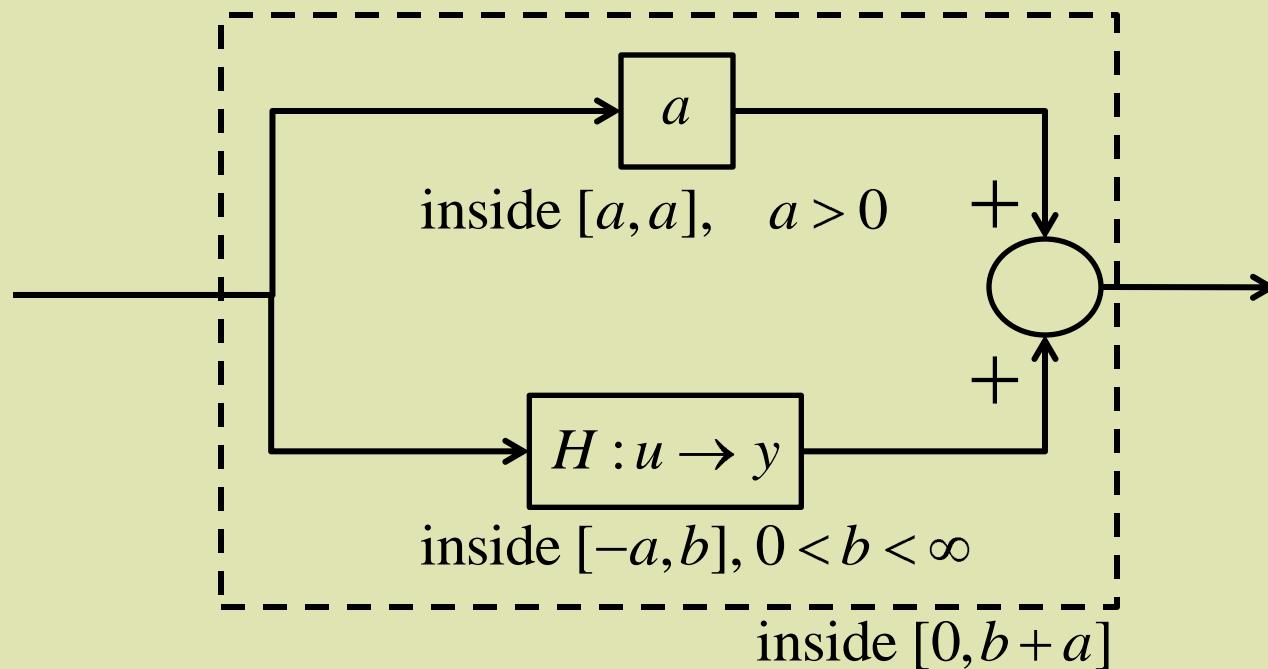


Conclusions

- Demonstrated how to interconnect redundant controllers in a resilient manner
- Tolerates both passive-faults and denial-of-service attacks w/o needing detection
- Highly unstable controllers will destabilize network w/o detection
- However, if detection occurs, isolation can be implemented in a transparent manner
- Detecting de-stabilizing controllers in the presence of different networking delays among controllers is fundamental research question.

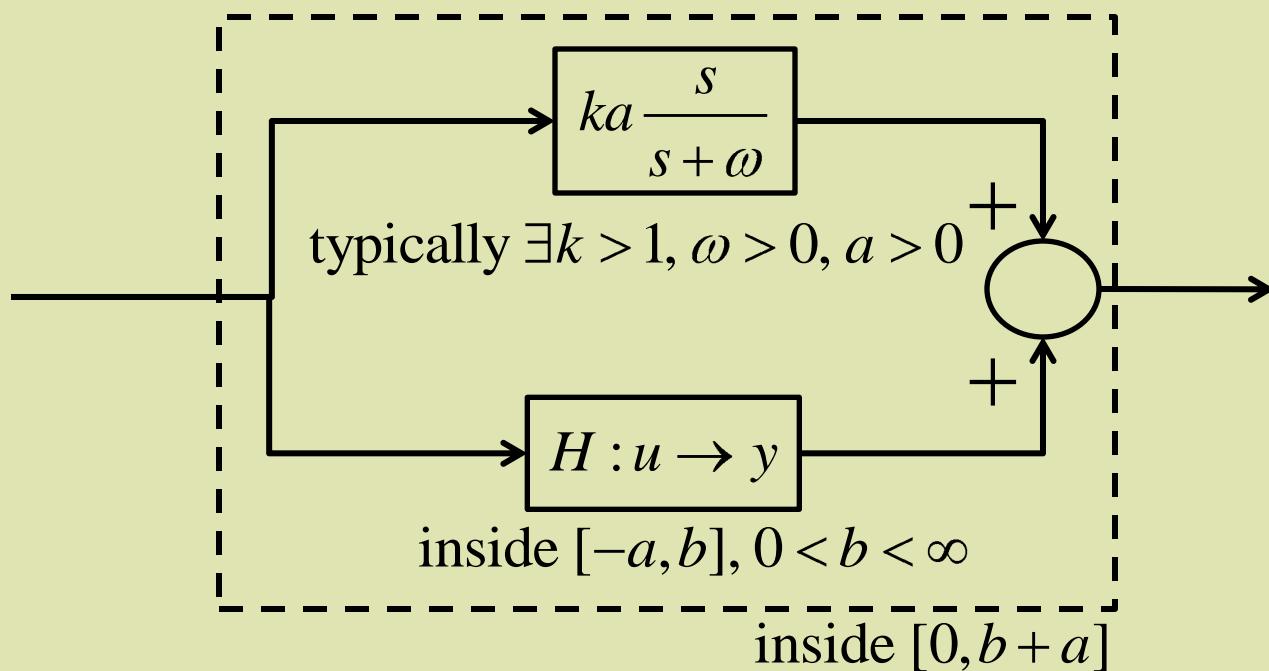


How to Make a Conic Sys. Passive



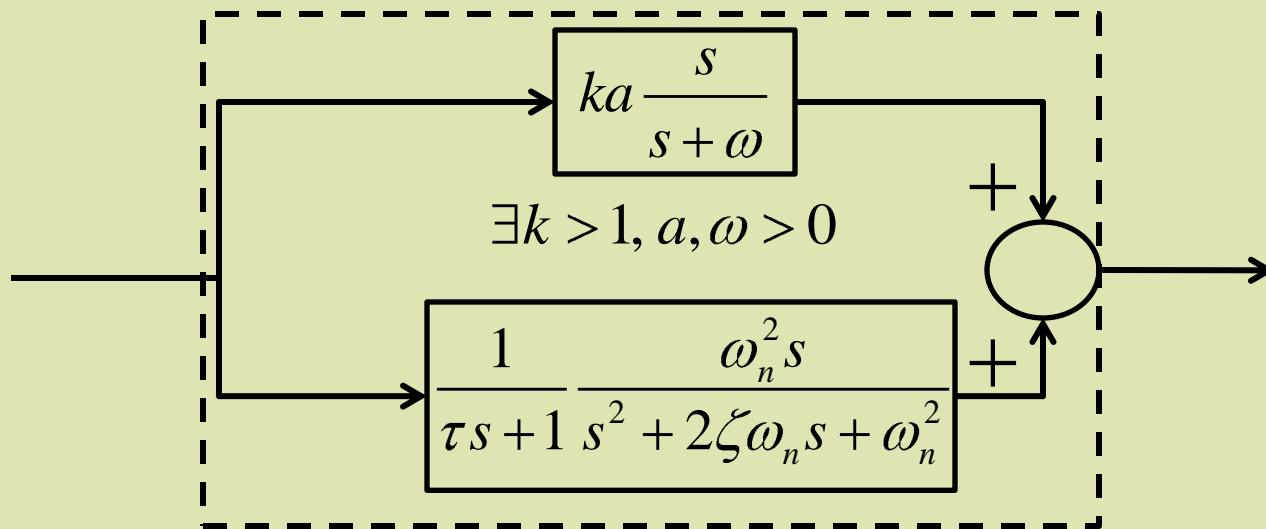


How to Make a Conic Sys. Passive





How to Make a Conic Sys. Passive





Additional Reading

- Kottenstette, N., and N. Chopra, "Lm2-stable digital-control networks for multiple continuous passive plants", 1st IFAC Workshop on Estimation and Control of Networked Systems (NecSys'09), Venice, Italy, International Federation of Automatic Control, 09/2009. <http://www.isis.vanderbilt.edu/node/4101>
- Kottenstette, N., and N. Chopra, "Lm2-stable digital-control networks for multiple continuous passive plants", Technical Report, Nashville, TN, Institute for Software Integrated Systems, Vanderbilt University, pp. 1-14, 04/2009. <http://www.isis.vanderbilt.edu/node/4079>
- Kottenstette, N., J. Hall, X. Koutsoukos, P. J. Antsaklis, and J. Sztipanovits, "Digital Control of Multiple Discrete Passive Plants Over Networks", Technical Report, Nashville, TN, Institute for Software Integrated Systems, Vanderbilt University, pp. 1-14, 03/2009. (accepted with revisions IJSCC) <http://www.isis.vanderbilt.edu/node/4050>